Study on Quantitative Microstructure Analysis by Mathematical Morphology

	シュイ イエン
氏　　　　　名	徐　　岩
授　与　学　位	博士（工学）
学位授与年月日	平成３０年３月２７日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）金属フロンティア工学専攻
学位論文題目	Study on Quantitative Microstructure Analysis by Mathematical Morphology （数学的形態学手法による定量的ミクロ組織解析に関する研究）
指　導　教　員	東北大学教授　安斎　浩一
論文審査委員	主査 東北大学教授　安斎　浩一　東北大学教授　及川　勝成 東北大学教授　川崎　亮

論 文 内 容 要 旨

The progress of material science is the basis of progress of human civilization and the material microstructure analysis has been a concerned subject ever since the first usage of optical microscope to metal materials. Material microstructure always has significant influence on the properties. Usually, people pursue desired performance of a material by altering its microstructure. For instance, heterogeneous nucleating agent is mixed into the liquid aluminum alloys to promote the nucleation during the solidification process and thus achieve fine microstructure. Such kind of material is expected to outcome better mechanical performances. It has long been an issue to obtain information from material microstructure so that people can make an evaluation on the subsequent performance of the material. The conventional material microstructure evaluation methods comprise manual measurement and image processing measurement. In a typical measurement process of image processing measurement, there are four steps. Firstly, an optical grayscale image of the microstructure should be achieved in the image acquisition stage. Next, the grayscale image would be filtered to reduce noise in the pre-processing stage. Thirdly, phase of interest should be properly separated in the image segmentation stage. Finally, microstructure evaluation parameter would be measured in the measurement stage. The manual method opposes high effectiveness and accuracy. However, it calls for high time-consumption and labor-intensity. In contrast, image processing method highly improves the efficiency and relieves the workload. The problem is that the accuracy will be sacrificed when the microstructure is sophisticated. Mathematical morphology is a powerful theory to obtain high quality image processing result. Recently, it has been dramatically developed and applied to different research fields, such as biology, medicine, civil engineering, hydrology and so on. In material, mathematical morphology was reported to be used to measure grain size for sample shaped grains. However, few had been reported to use mathematical morphology to evaluate sophisticated shaped grains. Thus, image analysis methods were proposed to evaluate sophisticated shaped grains based on the mathematical morphology algorithms.

In chapter one, conventional image analysis methods were reviewed and introduced. The art of state in the image analysis for material microstructure evaluation was described. The development of mathematical morphology and the application of it on material microstructure evaluation were also explained. The motivation and objectives in this dissertation was explained.

In chapter two, an image analysis method for automatic primary grain size measurement of semi-solid slurry of aluminum alloys was developed. Semi-solid die-casting (SSD) is drawing attention because of its merits such as near net shape for complex castings, porosity free, tight tolerance and so on. Usually, the homogeneous distribution of primary grain size is desirable when preparing the semi-solid slurry. Thus, the evaluation of primary grain size distribution is of high importance for the preparation of semi-solid slurry. The morphology of semi-solid slurry is very complex, e.g. complex grain shape, huge amount of small secondary phase in eutectic phase. Conventional image processing method found it difficult to produce accurate grain size distribution histogram. Thus, we proposed a new image analysis procedure according to the image processing techniques and mathematical morphology algorithms. At the first step, eutectic grains were identified with opening algorithm. The kernel size of structuring element used in opening operation was visually and manually selected. It should be larger than the size of secondary α grain and smaller than the size of primary grain. Next, an image segmentation using marker-image prepared with Euclidean distance map (EDM) method was implemented to separate individual primary grains. The threshold used to prepare markers from EDM result also should be carefully selected so that it could generate separated markers for congregated grains and not generate excess markers for complex-shaped grains. Eutectic grains were eliminated by intersect the image segmentation result with opening result. Finally, a second implementation of watershed transformation was conducted to segment small isolated primary grains dispersed in the eutectic grains. The results showed that the proposed method well reduced the over-segmentation, which was very common in the conventional method using ultimate eroding point method to prepare marker-image. As a result, the proposed method presented much better coincidence with the manual result. Subsequently, influence of image quality was investigated using bad quality image. The results showed that the combining application of black top hat (BTH) transformation and proposed method generated the most decent result to the manual method. The application of proposed method without BTH on bad quality image still produced better result than the conventional method and the conventional method with BTH transformation. Generally, the proposed method greatly improved the measuring accuracy for primary grain size in aluminum alloys. And, the combining operation with BTH transformation improved the robustness of the proposed method to different image quality.

In chapter three, an image analysis method for metal particle aspect ratio measurement has been proposed in this chapter. In contrast to the monotonous metal or ceramic materials, metal-ceramic compound opposes high strength, high toughness, good high temperature performance, thermal and electrical conductivity at the same time. When manufacturing the compound, metal particles would be milled with the ceramic matrix. The metal particles became longer than thinner when the speed is larger or the milling time is longer. In order to achieve high aspect ratio metal particles, people sought to use high rotation speed and high milling time. Aspect ratio is used to characterize the elongation effect of metal particles during the milling process. In this chapter, the improvement on the measuring of metal particle aspect ratio comprises of two parts. The first one is the image segmentation method for metal particles and the second one is the aspect ratio evaluating method. Conventional image segmentation method for aspect ratio is based on watershed transformation using automatic marker-image preparation method. It either over-segmented or under-segmented the metal particles in glass matrix. Thus, we used manual method to prepare the marker-image. The results showed that the manual method produced much better result in contrast to the watershed with UEP method and the method in chapter 2. The next improvement is about the aspect ratio evaluation method. The conventional aspect ratio evaluating method is fit ellipse method. It worked well for the straight striped metal particles, however, under-estimated those with bended strip shapes. In this chapter, two new image analysis methods for aspect ratio evaluation have been proposed. The first one is maximum inscribed circle (MIC) area method. The application result on manually drawn shapes showed this method had high accuracy for oval-like shapes but had systematic error for rectangle-like shapes. The application of this method on actual image showed that it yielded better result than fit ellipse method. The second one is major and minor axis length method. This method extracted the major and minor axis of the metal particle with mathematical morphology method. The major axis was estimated with skeletons extracted by thinning algorithm. The thinning result was not acceptable as there were many short branches on the result. We proposed a moving frontier method to cut off the short branches. Moving frontier method assumed water was poured into the skeleton from one endpoint, and flowed towards the other endpoints. When the water arrived at one endpoint, the flowing routine would be recorded. When the water frontier met a loop, the short routine to the next node would be used as part of the major axis. Water frontier would be poured from every endpoint and finally the longest routine will be taken as the major axis. The diameter of MIC was seen as the minor axis length. The comparison result of aspect ratio for individual metal particles showed that the proposed method produced much more accurate result than the conventional method, no matter the metal particle shape is straight strip or bended strip. The mean value for the individual metal particles in several images also proved that the proposed method produced closer result to the manual result than the conventional method.

In chapter four, we proposed an image analysis method for semi-automatic measurement of secondary dendrite arm space (SDAS) and dendritic cell size (DCS) based on mathematical morphology. SDAS is an important parameter to analyze the local cooling rate in the solidification process. Conventional method found it difficult to evaluate the SDA center lines. DCS correlates to the ductility of the alloy. Conventional image processing method found it difficult to measure SDAS and DCS individually. In this chapter, a semi-automatic SDAS and DCS measuring method is proposed based on mathematical morphology algorithms. Firstly, a human subjective preparation of marker-image was conducted and used in watershed transformation. The segmentation result showed that the semi-automatic segmentation well achieved individual secondary dendrite arms. Secondly, the center lines of the secondary dendrite arms were estimated with moving frontier method and least square method. As the center lines were the fit lines of the dendrite arm skeletons, the program in this chapter could help to improve the objectivity of center lines. The comparison of individual SDAS result with conventional intercept method, proposed method and manual method shows that the proposed method yielded closer result to the manual result. The mean SDAS result also proves that the proposed method could give better result. DCS of the dendrite was also measured with proposed method in this chapter. The conventional method cannot measure the DCS. Therefore, only the results of proposed method and manual method were compared. It showed that the proposed method produced accurate DCS result. Dendrite morphology affects the accuracy of SDAS measurement. In this chapter, we selected 8 samples containing different types of dendrite morphology. The results showed that the proposed method could give very close result to the manual result for dendrite morphology with inter-dendritic phase either coarsened or not coarsened. However, when the dendrite arm shape is round-like, the result of the proposed method appeared unsteady accuracy. When the dendrite arm edge is not clear, the proposed method still yielded good result while the conventional intercept method presented larger variation.

In chapter five, the main contents in every chapter were summarized.

In this dissertation, mathematical morphology algorithms were used to analyze the microstructure of primary α grain in Al alloy, metal particle shape in metal-ceramic and SDAS in Al alloys. The results showed that it outcomes the conventional image processing methods.

論文審査結果の要旨

材料の特性は様々な因子によって決定されるが、中でも材料のミクロ組織がどのような形態を有するかが重要であることは、よく知られている。本論文は、従来法では適用困難であった複雑な材料組織の定量的評価を、数学的形態学手法を用いることによって可能とすべく、種々の検討を加えた結果についてまとめたものである。

第1章は序論で、従来法による定量的ミクロ組織解析の限界と、医療画像や鉱物の組織解析の分野で発展してきた数学的形態学手法による定量的画像解析手法の現状と、その材料学分野への適用可能性について述べている。

第2章は、最近注目を集めている鋳造用Al-Si合金による半凝固ダイカスト法にて得られる特異な複雑形状初晶 Al の数学的形態学手法による定量的評価方法について検討した結果について述べている。この半凝固組織は、数十ミクロン程度の球状の微細初晶 Al と数ミクロン～数十ミクロン程度の球状の超微細初晶 Al と、残りの部分を占める Al と Si の共晶組織となることが知られており、微細及び超微細な初晶 Al の分布が、鋳造後のアルミ合金部品の機械的特性を決定することが知られている。しかし従来法では、平均初晶粒径を定量的に見積もることができても、初晶粒径毎の粒数分布を調べることは困難であった。そこで、Al-Si 共晶中の Al 粒を除外し、微細および超微細な初晶 Al のみを初晶粒径毎の粒数分布として定量的に評価できる手法として、数学的形態学手法に分類される、Euclidean Distance Map(EDM)法と、Black Hat Top(BHT)法を組み合わせることで、手作業による定量評価とほぼ同様な定量評価が可能であることを見いだした結果について述べている。

第3章は、ガラス中に扁平形状のニクロム片が分散した電気抵抗材料組織の数学的形態学手法による定量評価について検討した結果について述べている。この複合材料は、従来は電車などに用いられてきた鋳鉄による電気抵抗器の軽量化を目的として開発中の材料で、混入するニクロム片の個数やアスペクト比を変更することで電気抵抗値を制御できるという特徴がある。従来法では、このようなアスペクト比が大きい扁平した形状を定量評価することは、きわめて困難で有り、楕円を用いてアスペクト比を評価せざるを得なかった。しかし、本複合材中のニクロム片は、屈曲していたり、きわめて大きなアスペクト比を持つため、手作業による評価結果との誤差がきわめて大きいという欠点があった。そこで、アスペクト比の大きな屈曲したニクロム片の長軸長さと短軸長さを手作業に近い精度で求めることができる数学的形態学手法に基づく新規なアルゴリズムを考案した。

第4章は、金属組織の冷却速度の推定に用いられる樹枝状結晶の二次枝間隔（DASII）を半自動的に定量評価できるように、第2章および第3章の結果を応用したアルゴリズムを提案・適用した結果について述べている。

第5章は、総括である。

以上のように、本論文は、金属や複合材料の組織を精度良く定量解析することができる数学的形態学手法に基づく新規な手法について提案したものであり、金属フロンティア工学の発展に寄与するところ少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。